

Oscillations Above Sunspots and Faculae: Height Stratification and Relation to Coronal Fan Structure

N.I. Kobanov, D.Y. Kolobov, and A.A. Chelpanov

Institute of Solar-Terrestrial Physics

of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

email: kobanov@iszf.irk.ru

[This article was firstly published in *Solar Physics* [DOI](#)]

Abstract

Oscillation properties in two sunspots and two facular regions are studied using Solar Dynamics Observatory (SDO) data and ground-based observations in the Si I 10827 Å and He I 10830 Å lines. The aim is to study different-frequency spatial distribution characteristics above sunspots and faculae and their dependence on magnetic-field features and to detect the oscillations that reach the corona from the deep photosphere most effectively. We used Fast-Fourier-Transform and frequency filtration of the intensity and Doppler-velocity variations with Morlet wavelet to trace the wave propagating from the photosphere to the chromosphere and corona. Spatial distribution of low-frequency (1–2 mHz) oscillations outlines well the fan-loop structures in the corona (the Fe IX 171 Å line) above sunspots and faculae. High-frequency oscillations (5–7 mHz) are concentrated in fragments inside the photospheric umbra boundaries and close to facular-region centers. This implies that the upper parts of most coronal loops, which transfer low-frequency oscillations from the photosphere, sit in the Fe IX 171 Å line-formation layer. We used dominant frequency *vs.* distance from barycenter relations to estimate magnetic-tube inclination angle in the higher layers, which poses difficulties for direct magnetic-field measurements. According to our calculations, this angle is $\approx 40^\circ$ in the transition region around umbra borders. Phase velocities measured in the coronal loops' upper parts in the Fe IX 171 Å line-formation layer reach $100 - 150 \text{ km s}^{-1}$ for sunspots and $50 - 100 \text{ km s}^{-1}$ for faculae.

1 Introduction

The intensive study of oscillations observed in the solar atmosphere has lasted half a century. Many new facts about the origin and properties of oscillations have been obtained. One of the relevant problems is the interaction mechanism between the solar magnetic field and oscillations. According to early studies, the oscillation properties in the magnetic-field regions differ significantly from those observed in non-magnetic ones (Howard, Tanenbaum, and Wilcox, 1968; Balthasar and Wiehr, 1984; Lites, 1984; Kobanov, 1985).

The most noticeable magnetic-field regions on the Sun are sunspots and faculae. Magnetic structure of a single regularly formed sunspot has circular symmetry. Magnetic field is vertical in the center of a sunspot. The inclination increases with distance from the barycenter, and the field becomes almost horizontal in the outer penumbra. This feature makes sunspots the most attractive objects to study the relationship between the oscillatory-wave process properties and the magnetic field topology.

The study of oscillations in the lower layers of the solar atmosphere has revealed the decrease in dominant frequency with distance from the sunspot center (Rimmele, 1995; Sigwarth and Mattig, 1997; Kobanov, 2000; Kobanov and Makarchik, 2004). A peculiar property of sunspots is the existence of running penumbral waves (RPW), which are readily detected in the sunspot chromosphere (Beckers and Tallant, 1969; Giovanelli, 1972; Zirin and Stein, 1972). Two scenarios were proposed to interpret RPWs. According to the first one – the trans-sunspot wave scenario – the waves propagate from sunspot umbrae to penumbrae along an almost horizontal trajectory (Alissandrakis, Georgakilas, and Dialetis, 1992; Tsiropoula, Alissandrakis, and Mein, 2000; Tziotziou *et al.*, 2004, 2006). According to the second one – the visual pattern scenario – the waves propagate from the lower layers to the upper ones along a path with different angles. When observing the chromosphere, one sees an illusion of horizontal propagation (Rouppe van der Voort *et al.*, 2003; Bogdan and Judge, 2006; Bloomfield, Lagg, and Solanki, 2007; Kobanov *et al.*, 2009).

Oscillations in sunspots and faculae have combined and individual properties. For example, studies of the line-of-sight (LOS) velocity showed that five-minute band oscillations dominate in the photosphere of sunspot umbrae (Howard, Tanenbaum, and Wilcox, 1968; Bhatnagar, 1971; Thomas, Cram, and Nye, 1982; Balthasar and Wiehr, 1984) and faculae (Orrall, 1965; Howard, 1967; Sheeley and Bhatnagar, 1971); the amplitude of the oscil-

lations is suppressed relative to the undisturbed regions. Three-minute-band oscillations dominate in the chromosphere above spot umbrae (Beckers and Tallant, 1969; Kneer, Mattig, and von Uexkuell, 1981; Lites, 1984, 1986; Zhugzhda and Sych, 2014), while the facular chromosphere preserves five-minute oscillations and even reveals lower-frequency oscillations (Orrall, 1965; Howard, 1967; Teske, 1974; Blondel, 1971; Cram and Woods, 1980; Balthasar, 1990; Kobanov and Pulyaev, 2007).

The present opinion is that coronal five-minute oscillations are observed mainly above faculae and the chromospheric network (De Moortel, Ireland, and Walsh, 2000; Centeno, Collados, and Trujillo Bueno, 2006; Vecchio *et al.*, 2007), while three-minute oscillations in the solar corona are related to sunspots (O’Shea, Muglach, and Fleck, 2002; Doyle, Dzifčáková, and Madjarska, 2003). Three-minute oscillations above sunspots in the microwave range were observed with a 50-second delay compared with the chromospheric oscillations (Abramov-Maximov *et al.*, 2011).

Now excellent Solar Dynamics Observatory (SDO) data allow us to study mode properties in sunspots and faculae at different heights from the photosphere to the corona (Reznikova and Shibasaki, 2012; Reznikova *et al.*, 2012; Kobanov and Chelpanov, 2014).

Altitudinal cuts of the frequency spatial localization allow us to trace the path of wave perturbations. In the future, this technique can be used to determine magnetic-field inclination in the transition zone and the low corona using an alternative method (Jess *et al.*, 2013).

Fan structures are often observed in the corona above sunspot and faculae. These structures are seen especially clearly in the Fe IX 171Å line. It is possible to determine the frequency of the waves traveling along fan structures by comparing the spatial distribution (power localization) of selected frequency waves with the Fe IX 171Å line images of these regions. The relation between fan structures and waves is the subject of many studies. Marsh and Walsh (2006) found that three-minute umbral oscillations propagate directly into coronal loops. Similar conclusions have been made by Jess *et al.* (2012), who demonstrated that coronal loops are anchored in the photospheric umbral dots with enhanced intensity of three-minute oscillations. Earlier Brynildsen *et al.* (2004) showed that three-minute oscillations in the corona were confined to the narrow domain that corresponded to the sunspot umbra boundary at the photospheric level. These oscillations are suppressed in fan structures. Wang, Ofman, and Davila (2009) revealed 12- and 25-minute oscillations in coronal fans above sunspots and identified them as slow magnetoacoustic

waves. Kobanov, Chelpanov, and Kolobov (2013) supported the conclusions made by Brynildsen *et al.* (2004) concerning three-minute oscillations, and detected waves with periods of 12–15 minutes propagating from the penumbral photosphere to the coronal fans.

2 Methods

We used both space- and ground-based telescope observations that cover the same active regions at the same temporal intervals. SDO has three instruments onboard: the Atmospheric Imaging Assembly (AIA), the Helioseismic and Magnetic Imager (HMI) and Extreme Ultraviolet Variability Experiment (EVE), more details can be found in Lemen *et al.* (2012); Scherrer *et al.* (2012); Woods *et al.* (2012). The first provides data in a wide range of UV spectral lines, which cover heights from the photosphere to the corona. The intensity image series have cadences of 12 seconds for all but two lines: the 1600 Å and 1700 Å bands' cadence is 24 seconds. We chose four bands for the analysis. The coronal heights are represented by the Fe IX 171 Å and Fe XII, XXIV 193 Å lines. The other two are the continuum 1700 Å (the upper photosphere) and He II 304 Å (the transition region) lines, whose formation heights are the closest to those of the Si I 10827 Å and He I 10830 Å lines, which we used in the ground-based observations.

The second instrument, HMI, provides intensity, Doppler velocity, and magnetic field data obtained using the Fe I 6173 Å line with a 45 second cadence. This line is formed in the photosphere at a height of 100–150 km (Fleck, Couvidat, and Straus, 2011; Parnell and Beckers, 1969).

The ground-based observations were obtained with the solar telescope at the Sayan Solar Observatory located at an altitude of 2000 m. The telescope is elevated six meters above the ground and is equipped with a special system to suppress atmospheric turbulence (Hammerschlag and Zwaan, 1973). The telescope contains a coelostat, with the effective diameter of its main mirrors being 800 mm and a guiding system that keeps the Sun's image on the spectrograph slit with an accuracy of one arcsec. We used a Princeton Instruments RTE/CCD camera (256×1024). One element corresponded to a spatial resolution of 0.23 arcsecs along the entrance slit of the spectrograph and to 7 mÅ in the direction of the spectrograph dispersion. The observations provided a series of spectrograms with a cadence of 3 seconds containing the He I 10830 Å and Si I 10827 Å spectral lines. For details, see Kobanov *et al.*

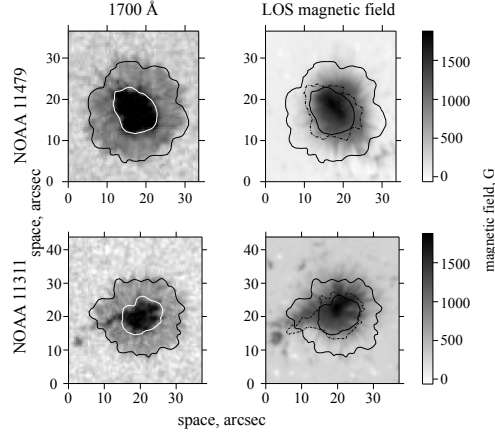


Figure 1: Sunspots under investigation. Sunspot images in the 1700 Å band (left), magnetograms (right). The inner and outer penumbra boundaries (black and white solid lines) are outlined by the 0.1 and 0.5 quiet Sun 1700 Å band intensity levels. Zero level corresponded to the lowest umbral intensity. The dashed isolines mark the regions where the magnetic field inclines at 45° to the surface normal.

(2013).

3 Results

3.1 Oscillations and Fan Structures Above Sunspots

Active regions NOAA 11311 and 11479 are single, round, medium-sized sunspots (see Figure 1). We observed them near the central meridian, which allowed us to minimize the projection effect on the analysis of oscillations at different heights. The domains studied included sunspots and the neighboring regions up to 5–10'' from the outer penumbra borders, since sunspots affect the oscillation characteristics of these regions (Kobanov, 2000).

Figure 2 shows the dominant frequency for every spatial element of the sunspots at several heights: Fe I 6173 Å, 1700 Å, He II 304 Å, and Fe IX 171 Å bands. The frequency determination was performed as follows. Firstly, the FFT intensity spectrum for each 0.6''×0.6'' domain was obtained. Preparing the signals for the FFT analysis, we subtracted an average intensity and applied a \cos^2 bell filter to minimize effects of abrupt endings. Then, the integral power in a 1 mHz rectangular window was calculated. The window

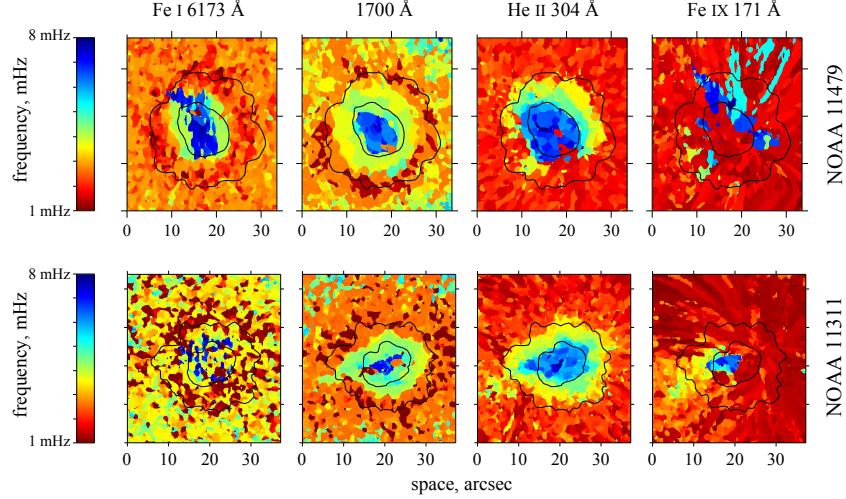


Figure 2: Spatial distributions of dominant frequencies from the photosphere to the corona. The black closed lines mark the inner and outer penumbral boundaries.

was moved throughout the spectrum with a 0.02 mHz step giving a set of values. The frequency corresponding to the maximum value was taken as the dominant one for the particular spatial domain. This representation is a convenient way to obtain a picture of the spatial distribution of oscillation frequencies above the sunspots under study. Five-minute oscillations dominate in the lower photosphere (the Fe I 6173 Å line), forming typical fragmented structure in the umbrae and the neighboring outer penumbra regions. Photospheric three-minute oscillations in sunspot NOAA 11311 are located mainly along the umbra boundary instead of the umbral central part, where these oscillations are located in the 1700 Å, He II 304 Å, and Fe IX 171 Å bands. This corresponds to our earlier results (Kobanov *et al.*, 2011; Kobanov, Chelpanov, and Kolobov, 2013). Five-minute oscillations are located in an annular zone around the sunspot center, which expands beyond the umbra boundaries with increasing height in both sunspots. Low-frequency oscillations start in the lower photosphere of the penumbra (left panels in Figure 2). Such a topology of the frequency distribution height cuts supports the concept explaining RPW as a “visual pattern” (Rouppé van der Voort *et al.*, 2003; Bloomfield, Lagg, and Solanki, 2007; Kobanov *et al.*, 2009). In the upper layers of the solar atmosphere, the field of view is mostly occupied by the low-frequency oscillations marked in red (Figure 2), whereas the high-frequency oscillations marked with blue color reside within the inner-penumbral boundaries. The

presence of the low-frequency inclusions inside the umbrae can probably be explained by fine-structure irregularities of the magnetic field. One should note that Figure 2 does not give the real picture of the oscillation power; it merely shows the spatial distribution of the frequencies instead. Circular-shaped frequency spatial localization allowed us to plot the frequency *vs.* distance from barycenter for three height levels: Fe I 6173 Å, 1700 Å, He II 304 Å (see Figure 3). White-light images were used to find barycenters of the sunspots. Then, using the data in Figure 2, we calculated a mean frequency value $[F(r)]$ averaged over the points located at distance r from the barycenter (Figure 3). Each point of the curves was determined as described. The radial spatial step was chosen to be $0.6''$. Similarly, the longitudinal magnetic field $[B_{||}]$ in Figure 3 and the absolute value of the magnetic-field inclination in Figure 4 (solid lines) were plotted against the distance from the barycenter. Magnetic-field inclination angle $[\varphi]$ to the solar-surface normal was calculated using SDO/HMI data as described by Borrero *et al.* (2011) and converted following the formalism of Gary and Hagyard (1990). It is of interest to compare the derived dependencies with the cut-off frequency for the waves, using the slow magnetoacoustic wave approximation. For this purpose, we used the following equation (McIntosh and Jefferies, 2006; Botha *et al.*, 2011):

$$f_c = \frac{g_0 \gamma \cos \varphi(r)}{4\pi v_s} \quad (1)$$

where f_c is the cut-off frequency; $g_0=274 \text{ m s}^{-2}$ is the gravitational constant; v_s is the speed of sound; $\gamma = \frac{5}{3}$ is the adiabatic index; $\varphi(r)$ is the dependence of inclination angle on the barycenter distance. Finally, we obtain the dashed curves in Figure 3 expressing the dependence of f_c on the barycenter distance for both sunspots.

Analyzing the plots in Figure 3, one can see several features: curves of the lowest atmospheric layers (Fe I 6173 Å and 1700 Å) show a jump. This is typical for both sunspots and is thus unlikely to be an artifact. The curves expressing frequency *vs.* distance from the barycenter do not coincide with those for f_c calculated using Equation (1). This is especially evident in the umbra, where the f_c curve is almost horizontal. Note that more correspondence is found for the $B_{||}$ curve in Figure 3 (upper panels). All of the curves approach each other in the middle parts of the penumbrae. This implies that the 3–3.5 mHz oscillations observed in the corresponding penumbra regions prevail at these heights. Probably, this circular penumbral

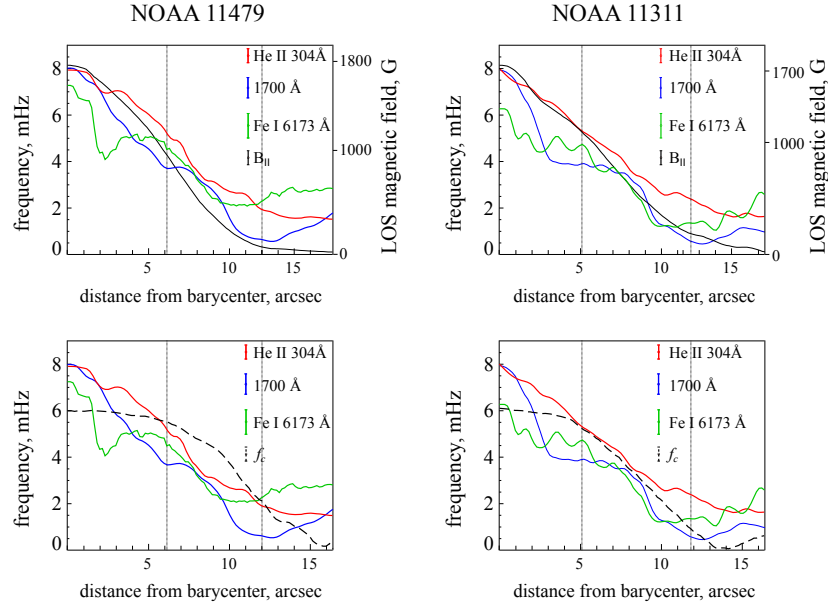


Figure 3: Dominant frequency as a function of distance from sunspot barycenters $[F(r)]$. Green line is Fe I 6173 Å; blue, 1700 Å; red, 304 Å. Black solid lines in the top panels represent LOS magnetic field as a function of distance from sunspot barycenters. The dashed lines in the bottom panels represent cut-off frequency as a function of distance from sunspot barycenters deduced using Equation (1) for acoustic speed of 6.2 km s^{-1} at the 6173 Å line formation level. The vertical lines mark the inner and outer penumbral boundaries.

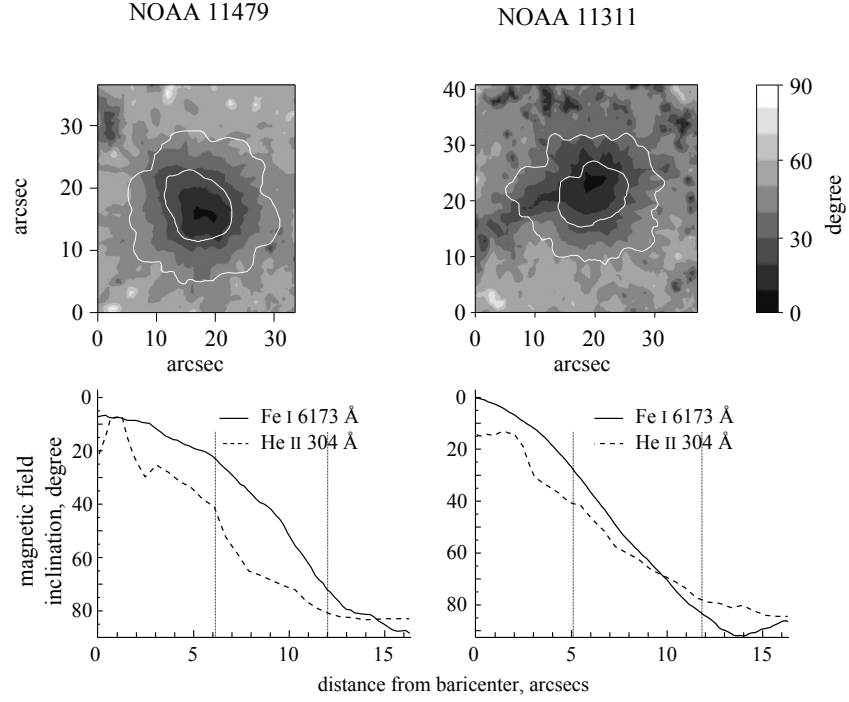


Figure 4: Magnetic-field inclination angle to solar normal gray-scale maps (upper row). The white closed lines mark the inner and outer boundaries of the penumbrae. Magnetic-field inclination angle to solar normal as a function of distance from sunspot barycenters (bottom row). The solid line was derived from vector magnetic-field measurements for the Fe I 6173 Å level (SDO/HMI). The dashed line was obtained using Equation (2) for the He II 304 Å level. The thin vertical lines mark the inner and outer penumbral boundaries.

zone is the very place to search for the upwardly propagating five-minute waves.

As [Jess *et al.* \(2013\)](#) showed, the dominant frequency distribution can be used to study physical conditions at corresponding heights (*e.g.* the magnetic-field inclination). Substituting f_c with $F(r)$ measured at the He II 304 Å line formation level in Equation (1), one can roughly estimate the magnetic-field inclination at this height:

$$\varphi = \arccos \left(\frac{4\pi v_s F(r)}{g_0 \gamma} \right) \quad (2)$$

Direct substitution of the dominant frequency $[f_c]$ for cut-off frequency $[F(r)]$ results in the ratio in the parentheses being greater than 1 for the high frequencies, which is unacceptable. Following [Yuan *et al.* \(2014\)](#), we used an empirical ratio $f_c = 0.81F(r)$ mHz–1 mHz for the 304 Å line. The result is suitable for qualitative assessments. To acquire more precise quantitative assessments the empirical ratio between f_c and $F(r)$ should be determined based on greater statistics. The results of such an estimation are presented in Figure 4, where the solid lines denote the magnetic field inclination angles derived with SDO/HMI in the photospheric Fe I 6173 Å line, and the dashed lines denote those derived using Equation (2) for the He II 304 Å line. The inclination reaches 40° at the inner penumbra boundary. Close values were obtained by other authors ([Jess *et al.*, 2012](#); [Reznikova *et al.*, 2012](#); [Kobanov, Chelpanov, and Kolobov, 2013](#)), who used different methods. In accordance with the derived plots, the magnetic-field inclination angle at the He II 304 Å line formation level rapidly increases in the umbrae and the adjacent penumbrae, and this rate gradually decreases in the outer penumbrae. This dependence corresponds to the plot presented by [Yuan *et al.* \(2014\)](#) for the He II 304 Å line.

As was noted above, the low-frequency oscillations occupy a greater area in the FOV with increasing height (Figure 2). At the same time, image fragments in the power maps become elongated in the radial direction. Frequency filtering provides clear visualization of spatial localization of different modes. Figure 5 presents 6–7 mHz filtered intensity signals corresponding to several heights. High-frequency oscillation locations at all levels are confined to the domains of the photospheric umbral boundaries. No fan structures are seen in this image. The situation is different for low-frequency oscillations of the 3–3.8 and 1–2 mHz bands. We refer to Figure 6, as we are most interested in finding the wave frequencies that penetrate into the corona and dominate in

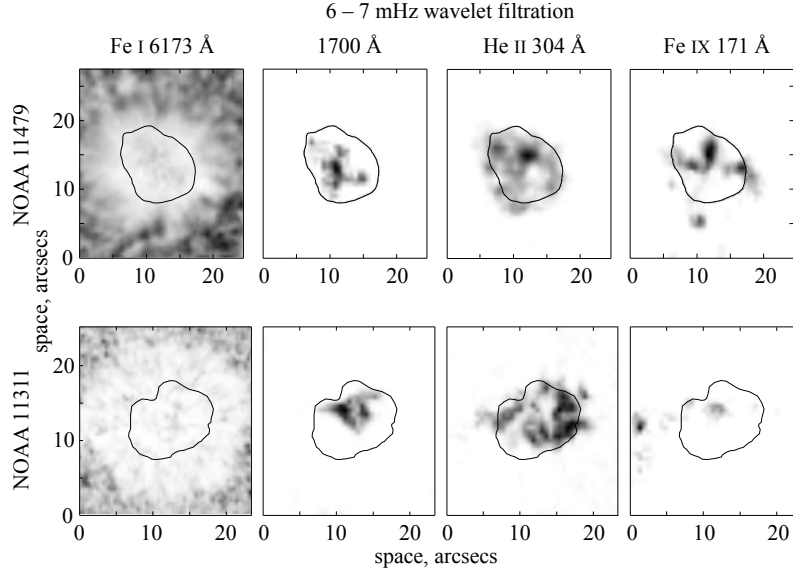


Figure 5: Spatial localization of high-frequency oscillations (6–7 mHz) at the different atmosphere levels. Darker regions correspond to more powerful oscillations. Solid lines mark the umbral boundaries.

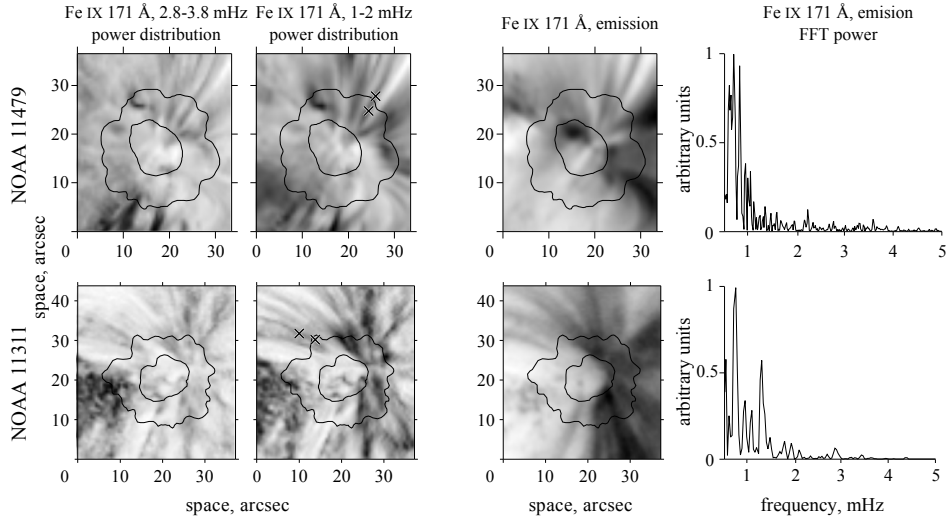


Figure 6: Fan structures in spatial localizations of low-frequency coronal oscillations (columns 1 and 2). Inverse sunspot images in the 171 Å line intensity (column 3). Intensity oscillation power spectra of the 171 Å line averaged over the fields of view (column 4).

the fan structures at the Fe IX 171Å line level. Left and middle panels in this figure show spatial distribution of the oscillation power in the 3–4 and 1–2 mHz bands respectively; right panels show the Fe IX 171Å intensity images, averaged over the entire time series. The intensity images were inverted for the convenience of visual comparison. One can see that coronal-fan structures are best reproduced in the middle panels showing the 1–2 mHz band oscillation power. Joint analysis of Figures 6 and 2 leads to the following conclusions: i) the 10–15 minute oscillations dominate in the corona above sunspots; ii) these oscillations are observed along the loops; thus, one can trace changes in their properties along the horizontal part of the loops and try to measure the propagation speed.

The crosses in the middle panel of Figure 6 show the points that were analyzed in detail. The power spectra for these points are shown in Figure 7. A correspondence between the spectra indicates that both of them belong to the same loop. Contrary to our expectations, the time delay between the signals from two points of the same loop was ambiguous, with variations in amplitude and sign over the whole time series. One of the possible explanations implies the existence of several thin and highly transparent coronal loops contributing to the signal. In spite of such a phase difference, the oscillations with close frequencies have similar power spectra. The averaged estimations give the following phase velocities: $120 \pm 25 \text{ km s}^{-1}$ for NOAA 11479 and $130 \pm 30 \text{ km s}^{-1}$ for NOAA 11311. Similar values were obtained by [Nightingale, Aschwanden, and Hurlburt \(1999\)](#); [Robbrecht *et al.* \(2001\)](#); [Marsh *et al.* \(2003\)](#).

3.2 Characteristics of Facular Oscillations

The analysis was performed using two faculae. Facula No.1 was observed on 6 October 2011 from 00:47 UT until 02:42 UT, with center coordinates S12E05. This facula is of special interest due to its proximity to sunspot NOAA 11311, which implies its direct connection through magnetic field arches. We observed facula region No.2 with coordinates N13W08 on 1 October 2011, from 03:41 UT until 05:06 UT. We identified this facula as not being connected with sunspots. The ground-based observations are spectrogram time series in the Si I 10827Å and He I 10830Å lines. The temporal resolution was 3.3 seconds, and the spatial resolution along the slit was 1–1.5'' on average. We chose the same SDO lines that we used for the sunspot analysis. Facular regions were confined by the 0.7 brightness isoline in the

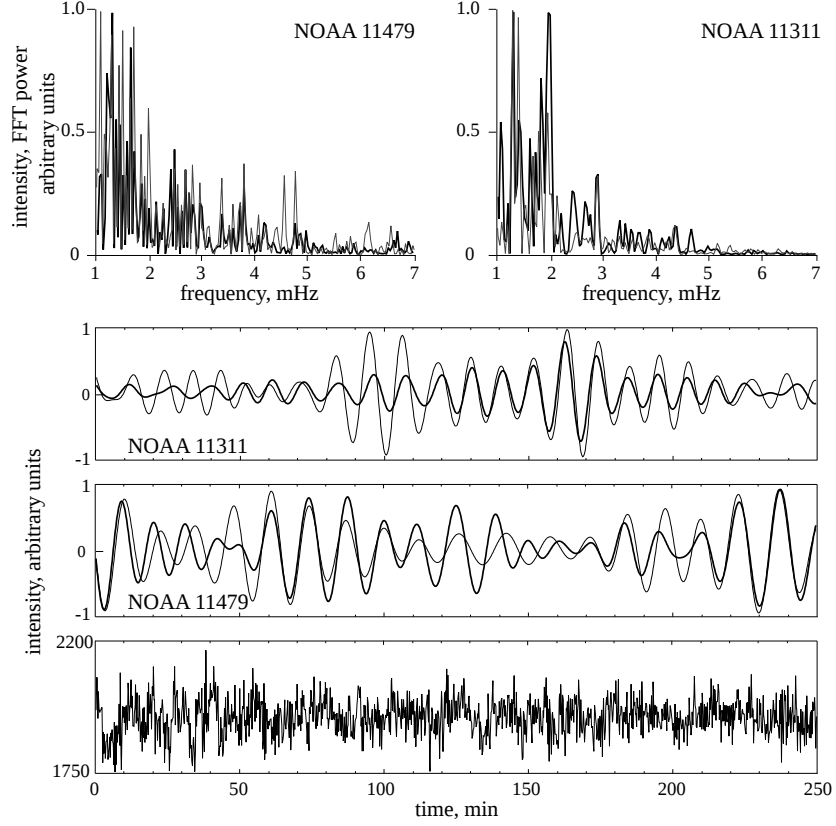


Figure 7: Oscillation behavior in coronal loops above sunspots. The top panels show intensity oscillation power spectra in the loop points marked with crosses in Figure 6. The results of frequency filtration are presented in the middle panels. The thick lines show spectra and signals at the points located further from the sunspot centers. The bottom panel shows an example of an original intensity signal (NOAA 11479).

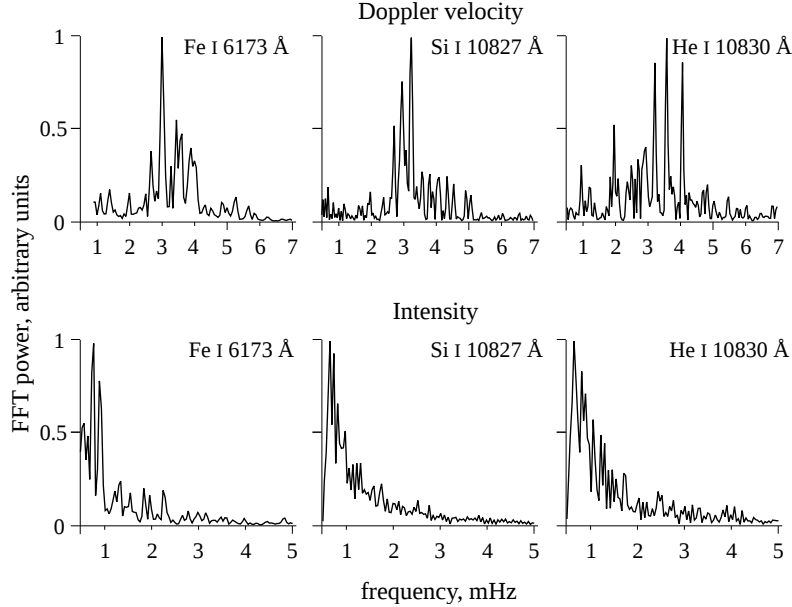


Figure 8: Power spectra of the LOS velocity (top panels) and intensity (bottom panels) oscillations. The signals were averaged over the area marked with the square box in Figure 10 (first column).

1700 Å band, where the 100 % brightness was considered to be the maximum facula-core brightness. The faculae have arbitrary shapes and lack radial symmetry. We intended to determine the frequency bands which prevail in the fan structures observed at the 171 Å line formation level, and to reveal their source as far as possible. To this end, we needed to study facular oscillation properties from the deep photosphere to the corona.

Information about oscillation parameters in the upper atmosphere of faculae is controversial. Koutchmy, Zhugzhda, and Locans (1983) observed periodic displacements of the coronal 5303 Å line at a height of 25 000–30 000 km above a facula. They revealed 300 seconds, 80 seconds, and 40 seconds periods. Using high spatial resolution observations, de Wijn, McIntosh, and De Pontieu (2009) found that three-minute periods prevail in the chromosphere above the facula core, while five-minute periods dominate on its periphery. This configuration is similar to that observed in sunspots. When studying five-minute oscillations in the X-rays above faculae, Didkovsky *et al.* (2011) concluded that they were related to global solar surface oscillations (*p*-modes) observed in the photosphere. Ofman, Nakariakov, and Deforest (1999) and

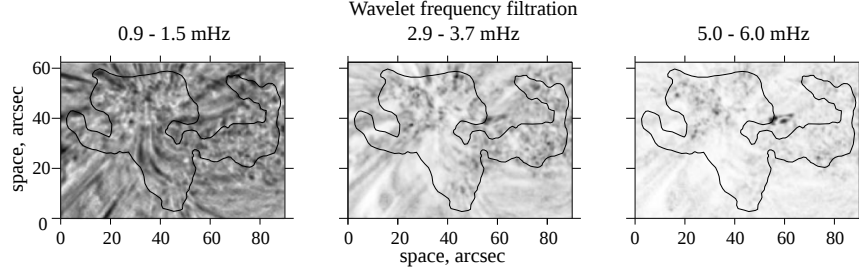


Figure 9: Spatial localization of the Fe IX 171Å line intensity oscillations for three frequency ranges. Darker regions correspond to more powerful oscillations. Solid lines mark the facular boundaries (0.7 brightness isoline in the 1700Å band).

Deforest and Gurman (1998) recorded 15-minute oscillations in the corona above polar faculae, which they explained as a manifestation of slow magnetoacoustic waves.

First, we analyzed characteristics of LOS-velocity oscillations observed at three heights: Fe I 6173Å – 200 km (Parnell and Beckers, 1969), Si I 10827Å – 540 km; He I 10830Å – 2000 km (Centeno, Collados, and Trujillo Bueno, 2009).

The observed LOS-velocity signals contain information about acoustic oscillations at these heights. Figure 8 shows the power spectra for the signals averaged over the area marked with a square in the middle part of Facula 2 in Figure 10 (first column, second panel). Both space (Fe I 6173Å) and ground-based (Si I 10827Å, He I 10830 Å) observations of LOS velocity show that the five-minute period is dominant in the photosphere and upper chromosphere (Figure 8, top row). The lower row in Figure 8 presents the intensity variation spectra in the same locations. All spectra are normalized to their maximum values. The five-minute oscillations are almost absent in the intensity spectra, while they dominate in the LOS-velocity spectra. The 0.7–1.2 mHz oscillations dominate in the intensity spectra of the lower photosphere. There have always been doubts about the solar origin of intensity oscillations in ground-based observations: are they a result of the Earth’s atmospheric turbulence? The photospheric spectra of space observations (Fe I 6173 Å) agree well with those of ground-based observations (Si I 10827 Å). The height difference between the formation levels (200 km and 540 km for the Fe I and Si I lines respectively) may explain the minor difference in details. At the same time, the photospheric and chromospheric ground-based spectra also differ,

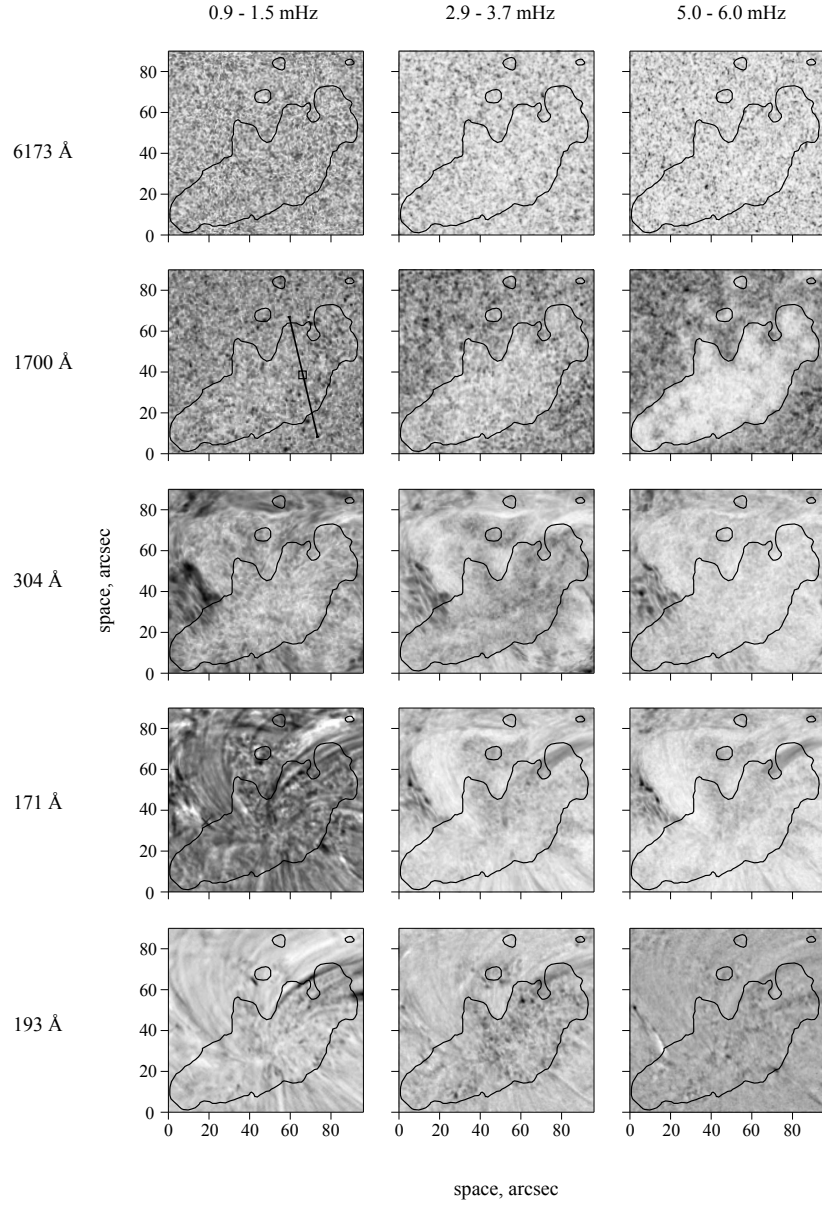


Figure 10: Spatial distribution of oscillation power above Faculae2 in the three frequency ranges for five atmosphere levels. Darker regions correspond to more powerful oscillations. Solid lines mark the facular boundaries.

which should not be the case if they are affected by the same artifact. These arguments confirm the solar origin of the low-frequency peak shown in the lower panels in Figure 8. The absence of such peaks in the LOS-velocity variation spectra may signify that two different types of oscillations coexist in the observed volume. The five-minute variations in the LOS-velocity signals are undoubtedly acoustic oscillations, and the $0.7 - 1.2$ mHz peaks are probably a sausage-mode manifestation.

Figure 9 shows how modes with different frequencies are distributed in the lower corona (the Fe IX 171 Å line). Spatial distributions of low-frequency oscillation power outlines fan-loop structures best. This similarity is less pronounced in the five-minute range and almost disappears in the three-minute range. The change in power spatial localization of these frequencies with height can be illustrated by the example of Facula 2 (Figure 10). At the lowest level (Fe I 6173 Å), the facula region is similar to the surrounding background at all frequencies (see Figure 10, upper row). At the temperature minimum level (the 1700 Å line) the decrease in oscillation power becomes evident, relative to the surrounding background. This is most apparent at high frequencies (Figure 10, the third panel in the second row). The oscillation-power distribution in the transition region (the He II 304 Å line) shows the first signs of elongated elements, which become a clearly expressed fan structure in the lower corona (Fe IX 171 Å) in the frequency range of $0.9 - 1.5$ mHz. This structure has reduced contrast at the Fe XII, XXIV 193 Å line formation height. At the level of the Fe XII, XXIV 193 Å line, the facula shows higher oscillation power relative to the adjacent regions at the highest level in the $2.8 - 3.8$ mHz and $5.0 - 6.0$ mHz ranges. Probably, this tendency is better developed higher above the Fe XII, XXIV 193 Å line formation height. This will be a subject for further research. The fact that spatial localization of low-frequency oscillations closely reproduces coronal-loop structures means that facular low-frequency oscillations penetrate to the corona through this very loop system. We observe the upper and, thus, the most horizontal parts of the loops at the Fe IX 171 Å line-formation level. Such a feature of the loop geometry gives an opportunity to analyze the oscillation spectral-phase characteristics in more detail. The marks in Figure 11 show points that we used to calculate the FFT power spectra. Figure 12 represents the spectra for each element pair ($1.2 \times 1.2''$ in size) located at individual loop. These spectra are convincing evidence of the fact that low frequencies dominate in loop structures at the 171 Å line formation height. May these oscillations exist outside loops as well? Figure 13 gives answers to this question, showing

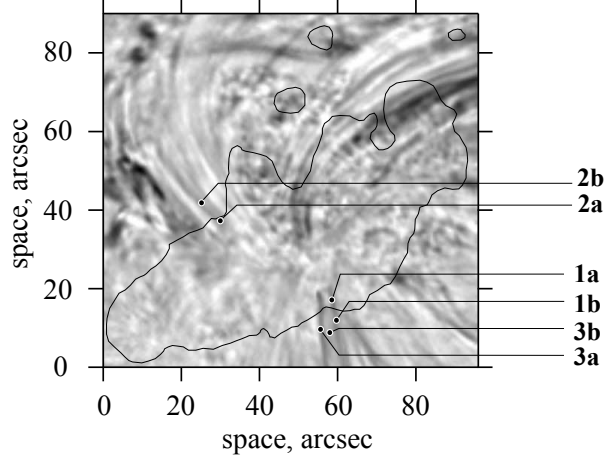


Figure 11: Manifestation of fan structures in spatial distribution of low-frequency coronal oscillations at the Fe IX 171Å line-formation height. The marks show the loop element pairs selected for the analysis.

the spectra for two spatial elements, one inside the loop and the other one $\approx 2''$ away from the loop. The oscillation inside the loop element is approximately five times higher than the background level. Spectral similarity for the loop elements gives hope that we are able to unambiguously measure the phase speed at the dominant frequency. However, the results of a similar analysis were ambiguous (Kobanov and Chelpanov, 2014). The phase speed based on the time-lag measurement varies from 50 km s^{-1} to 100 km s^{-1} with the average value of 60 km s^{-1} .

We performed a similar analysis for a loop connecting Facula 1 and sunspot NOAA 11311 (Figure 14). Note that the oscillation spectra in the loop’s footpoints 1 and 2 differ noticeably (Figure 15, the upper row). The spectra of the elements located fairly close to each other in the middle part of the loop show differences as well (Figure 15, lower row). Phase-speed measurements based on the signals at points 3 and 4 in the middle part of the loop are also ambiguous and yield values of $100\text{--}120 \text{ km s}^{-1}$. One can conclude that oscillation spectral-phase characteristics in the analyzed loop of Facula 1 considerably differ from those of Facula 2, which is caused by the NOAA 11311 influence. Figure 16 represents the maximum intensity variation values for three frequency bands at five heights. Both faculae show that the low frequencies dominate at all heights, and the largest intensity variation

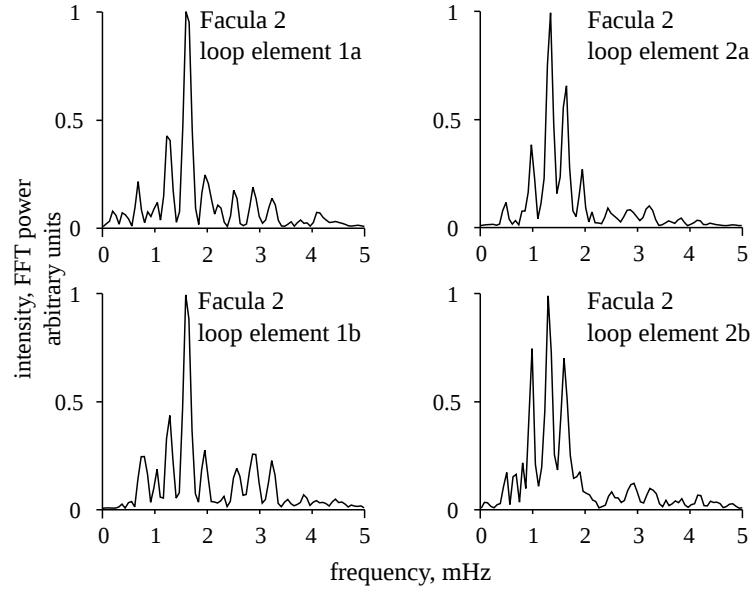


Figure 12: Oscillation power spectra for the loop elements marked in Figure 11.

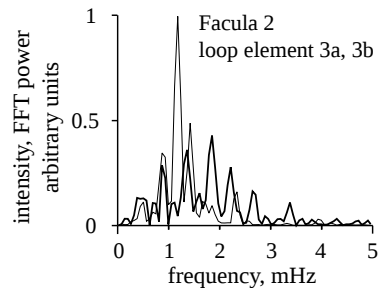


Figure 13: Oscillation power spectra for the points located inside (thin line) and outside (thick line) the loop.

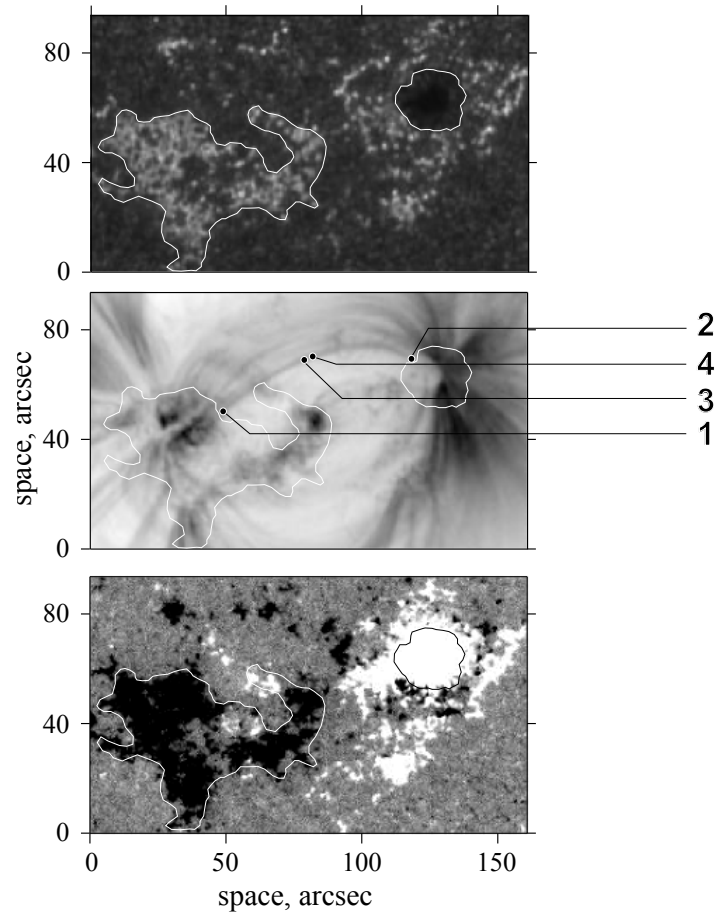


Figure 14: Sunspot NOAA 11311 and the adjacent facula. Top panel: the 1700Å band image; middle panel: 1–2 mHz oscillation wavelet power in the Fe IX 171Å line; bottom panel: LOS magnetogram. Darker regions correspond to more powerful oscillations. Solid lines mark the facular and sunspot's boundaries.

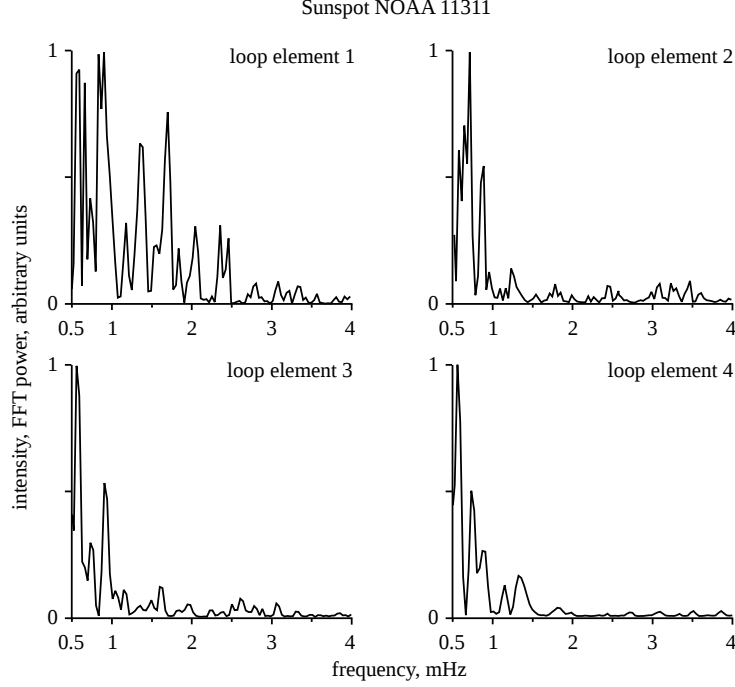


Figure 15: FFT power spectra. Oscillations detected at the points marked in Figure 14 (middle panel).

is detected in the transition region (the He II 304 Å line).

4 Conclusions

Low-frequency oscillations (1–2 mHz) in sunspots are concentrated in penumbrae forming annular areas, which expand with height. High-frequency oscillations (5–7 mHz) are concentrated in fragments located in areas confined to the photosphere umbra boundaries at all heights. Spatial distribution of low-frequency oscillations in the corona above sunspots and faculae reproduces the coronal fan structures well. This signifies that the upper parts of most coronal loops conducting 10–15 min oscillations are located within the Fe IX 171 Å line-formation layer, while three-minute and shorter-period oscillations possibly penetrate to higher coronal levels by other loops. The observation-based dominant frequency *vs.* distance from barycenter relations may be used to determine inclination of magnetic tubes in higher levels where

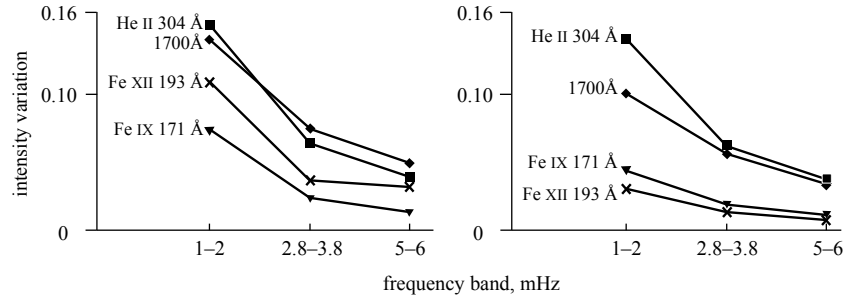


Figure 16: Intensity variation at the specified frequency band for four UV lines (normalized to unity). Left panel – facula No. 1, right panel – facula No. 2

it cannot be measured directly. The calculations show that this angle is close to 40° above the umbral borders in the transition region. Phase speeds measured in the coronal loops' upper parts at the Fe IX 171 Å line formation height reach $100\text{--}150\text{ km s}^{-1}$ for sunspots and $50\text{--}100\text{ km s}^{-1}$ for faculae. Intensity and LOS-velocity oscillation power spectra differ significantly in the facular lower atmospheric layers: spectra of intensity oscillations show the prevalence of the $0.7\text{--}1.2\text{ mHz}$ frequency oscillations; in those of LOS-velocity, the dominant oscillations are five-minute oscillations. Such spectra are typical for both ground-based and space observations. The absence of low-frequency peaks in LOS-velocity spectra may signify that two oscillation types coexist in the region under study. Amplitude of intensity oscillations is maximum in the transition region (He II 304 Å) above faculae.

Acknowledgements. The study was performed with partial support of the Projects No. 16.3.2, 16.3.3 of ISTP SB RAS. We acknowledge E. Korzhova for her help in preparing the English version of the article and the NASA/SDO science team for providing the data. We are grateful to an anonymous referee for the helpful remarks and suggestions.

References

- Abramov-Maximov, V.E., Gelfreikh, G.B., Kobanov, N.I., Shibasaki, K., Chupin, S.A.: 2011, Multilevel Analysis of Oscillation Motions in Active Regions of the Sun. *Solar Phys.* **270**, 175. doi:[DOI](#).
- Alissandrakis, C.E., Georgakilas, A.A., Dialetis, D.: 1992, Dynamic phenomena in the chromospheric layer of a sunspot. *Solar Phys.* **138**, 93. doi:[DOI](#).

- Balthasar, H.: 1990, The oscillatory behaviour of solar faculae. *Solar Phys.* **127**, 289. doi:[DOI](#).
- Balthasar, H., Wiehr, E.: 1984, Umbral oscillations measured in the Stokes-V inversion point. *Solar Phys.* **94**, 99. doi:[DOI](#).
- Beckers, J.M., Tallant, P.E.: 1969, Chromospheric Inhomogeneities in Sunspot Umbrae. *Solar Phys.* **7**, 351. doi:[DOI](#).
- Bhatnagar, A.: 1971, Fine-Scan Velocity and Magnetic- field Measurements in Solar Active Regions. *Solar Phys.* **16**, 40. doi:[DOI](#).
- Blondel, M.: 1971, Statistical Compared Studies of Velocity-Fields in a Facular Region and in two Quiet Re- gions of the Photosphere. *Astron. Astrophys.* **10**, 342.
- Bloomfield, D.S., Lagg, A., Solanki, S.K.: 2007, The Nature of Running Penumbral Waves Revealed. *Astrophys. J.* **671**, 1005. doi:[DOI](#).
- Bogdan, T.J., Judge, P.G.: 2006, Observational aspects of sunspot oscillations. *Royal Society of London Philosophical Transactions Series A* **364**, 313. doi:[DOI](#).
- Borrero, J.M., Tomczyk, S., Kubo, M., Socas-Navarro, H., Schou, J., Couvidat, S., Bogart, R.: 2011, VFISV: Very Fast Inversion of the Stokes Vector for the Helioseismic and Magnetic Imager. *Solar Phys.* **273**, 267. doi:[DOI](#).
- Botha, G.J.J., Arber, T.D., Nakariakov, V.M., Zhugzhda, Y.D.: 2011, Chromospheric Resonances above Sunspot Umbrae. *Astrophys. J.* **728**, 84. doi:[DOI](#).
- Brynildsen, N., Maltby, P., Foley, C.R., Fredvik, T., Kjeldseth-Moe, O.: 2004, Oscillations in the Umbral Atmosphere. *Solar Phys.* **221**, 237. doi:[DOI](#).
- Centeno, R., Collados, M., Trujillo Bueno, J.: 2006, In: Casini, R., Lites, B.W. (eds.) *Oscillations and Wave Propagation in Different Solar Magnetic Features, Solar Polarization 4, ASP Conference Series.* **358**, 465.
- Centeno, R., Collados, M., Trujillo Bueno, J.: 2009, Wave Propagation and Shock Formation in Different Magnetic Structures. *Astrophys. J.* **692**, 1211. doi:[DOI](#).
- Cram, L.E., Woods, D.T.: 1980, Models for Stellar Flares Based on the Physics of Solar Flares. *Bull. Am. Astron. Soc.* **12**, 914.
- De Moortel, I., Ireland, J., Walsh, R.W.: 2000, Observation of oscillations in coronal loops. *Astron. Astrophys.* **355**, L23.

- de Wijn, A.G., McIntosh, S.W., De Pontieu, B.: 2009, On the Propagation of p-Modes Into the Solar Chromosphere. *Astrophys. J. Lett.* **702**, L168. doi:[DOI](#).
- Deforest, C.E., Gurman, J.B.: 1998, Observation of Quasi-periodic Compressive Waves in Solar Polar Plumes. *Astrophys. J. Lett.* **501**, L217. doi:[DOI](#).
- Didkovsky, L., Judge, D., Kosovichev, A.G., Wieman, S., Woods, T.: 2011, Observations of Five-minute Solar Oscillations in the Corona Using the Extreme Ultraviolet Spectrophotometer (ESP) On Board the Solar Dynamics Observatory Extreme Ultraviolet Variability Experiment (SDO/EVE). *Astrophys. J. Lett.* **738**, L7. doi:[DOI](#).
- Doyle, J.G., Dzifčáková, E., Madjarska, M.S.: 2003, Coronal Oscillations above Sunspots? *Solar Phys.* **218**, 79. doi:[DOI](#).
- Fleck, B., Couvidat, S., Straus, T.: 2011, On the Formation Height of the SDO/HMI Fe 6173 Å Doppler Signal. *Solar Phys.* **271**, 27. doi:[DOI](#).
- Gary, G.A., Hagyard, M.J.: 1990, Transformation of vector magnetograms and the problems associated with the effects of perspective and the azimuthal ambiguity. *Solar Phys.* **126**, 21. doi:[DOI](#).
- Giovanelli, R.G.: 1972, Oscillations and Waves in a Sunspot. *Solar Phys.* **27**, 71. doi:[DOI](#).
- Hammerschlag, R.H., Zwaan, C.: 1973, An Efficient Wind Shield for the Protection of Telescopes. *Pub. Astron. Soc. Pac.* **85**, 468. doi:[DOI](#).
- Howard, R.: 1967, Velocity Fields in the Solar Atmosphere. *Solar Phys.* **2**, 3. doi:[DOI](#).
- Howard, R., Tanenbaum, A.S., Wilcox, J.M.: 1968, A new method of magnetograph observation of the photospheric brightness, velocity, and magnetic fields. *Solar Phys.* **4**, 286. doi:[DOI](#).
- Jess, D.B., De Moortel, I., Mathioudakis, M., Christian, D.J., Reardon, K.P., Keys, P.H., Keenan, F.P.: 2012, The Source of 3 Minute Magnetoacoustic Oscillations in Coronal Fans. *Astrophys. J.* **757**, 160. doi:[DOI](#).
- Jess, D.B., Reznikova, V.E., Van Doorselaere, T., Keys, P.H., Mackay, D.H.: 2013, The Influence of the Magnetic Field on Running Penumbra Waves in the Solar Chromosphere. *Astrophys. J.* **779**, 168. doi:[DOI](#).

- Kneer, F., Mattig, W., von Uexkuell, M.: 1981, The chromosphere above sunspot umbrae. III - Spatial and temporal variations of chromospheric lines. *Astron. Astrophys.* **102**, 147.
- Kobanov, N.I.: 1985, Narrowband spatial filtering in differential measurements of the line-of-sight velocity of the solar atmosphere. *Astron. Astrophys.* **143**, 99.
- Kobanov, N.I.: 2000, The properties of velocity oscillations in vicinities of sunspot penumbra. *Solar Phys.* **196**, 129. doi:[DOI](#).
- Kobanov, N.I., Chelpanov, A.A.: 2014, The relationship between coronal fan structures and oscillations above faculae regions. *Astron. Rep.* **58**, 272. doi:[DOI](#).
- Kobanov, N.I., Makarchik, D.V.: 2004, Pulsating Evershed Flows and Propagating Waves in a Sunspot. *Astron. Rep.* **48**, 954. doi:[DOI](#).
- Kobanov, N.I., Pulyaev, V.A.: 2007, Photospheric and Chromospheric Oscillations in Solar Faculae. *Solar Phys.* **246**, 273. doi:[DOI](#).
- Kobanov, N.I., Chelpanov, A.A., Kolobov, D.Y.: 2013, Oscillations above sunspots from the temperature minimum to the corona. *Astron. Astrophys.* **554**, A146. doi:[DOI](#).
- Kobanov, N.I., Kolobov, D.Y., Sklyar, A.A., Chupin, S.A., Pulyaev, V.A.: 2009, Characteristics of oscillatory-wave processes in solar structures with various magnetic field topology. *Astron. Rep.* **53**, 957. doi:[DOI](#).
- Kobanov, N.I., Kolobov, D.Y., Chupin, S.A., Nakariakov, V.M.: 2011, Height distribution of the power of 3-min oscillations over sunspots. *Astron. Astrophys.* **525**, A41. doi:[DOI](#).
- Kobanov, N., Kolobov, D., Kustov, A., Chupin, S., Chelpanov, A.: 2013, Direct Measurement Results of the Time Lag of LOS-Velocity Oscillations Between Two Heights in Solar Faculae and Sunspots. *Solar Phys.* **284**, 379. doi:[DOI](#).
- Koutchmy, S., Zhugzhda, I.D., Locans, V.: 1983, Short period coronal oscillations - Observation and interpretation. *Astron. Astrophys.* **120**, 185.
- Lemen, J., Title, A., Akin, D., Boerner, P., Chou, C., Drake, J., Duncan, D., Edwards, C., Friedlaender, F., Heyman, G., Hurlburt, N., Katz, N., Kushner, G., Levay, M., Lindgren, R., Mathur, D., McFeaters, E., Mitchell, S., Rehse, R., Schrijver, C., Springer, L., Stern, R., Tarbell, T., Wuelser, J.-P., Wolfson, C.J., Yanari, C., Bookbinder, J., Cheimets, P., Caldwell, D., Deluca, E., Gates, R.,

- Golub, L., Park, S., Podgorski, W., Bush, R., Scherrer, P., Gumm, M., Smith, P., Aufer, G., Jerram, P., Pool, P., Soufi, R., Windt, D., Beardsley, S., Clapp, M., Lang, J., Waltham, N.: 2012, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *Solar Physics* **275**(1-2), 17. doi:[DOI](https://doi.org/10.1007/s11207-011-9776-8). <http://dx.doi.org/10.1007/s11207-011-9776-8>.
- Lites, B.W.: 1984, Photoelectric observations of chromospheric sunspot oscillations. II - Propagation characteristics. *Astrophys. J.* **277**, 874. doi:[DOI](https://doi.org/10.1086/15200).
- Lites, B.W.: 1986, Photoelectric observations of chromospheric sunspot oscillations. III - Spatial distribution of power and frequency in umbrae. *Astrophys. J.* **301**, 992. doi:[DOI](https://doi.org/10.1086/15390).
- Marsh, M.S., Walsh, R.W.: 2006, p-Mode Propagation through the Transition Region into the Solar Corona. I. Observations. *Astrophys. J.* **643**, 540. doi:[DOI](https://doi.org/10.1086/50500).
- Marsh, M.S., Walsh, R.W., De Moortel, I., Ireland, J.: 2003, Joint observations of propagating oscillations with SOHO/CDS and TRACE. *Astron. Astrophys.* **404**, L37. doi:[DOI](https://doi.org/10.1051/0004-6361/200300037).
- McIntosh, S.W., Jefferies, S.M.: 2006, Observing the Modification of the Acoustic Cutoff Frequency by Field Inclination Angle. *Astrophys. J. Lett.* **647**, L77. doi:[DOI](https://doi.org/10.1086/50500).
- Nightingale, R.W., Aschwanden, M.J., Hurlburt, N.E.: 1999, Time Variability of EUV Brightenings in Coronal Loops Observed with TRACE. *Solar Phys.* **190**, 249. doi:[DOI](https://doi.org/10.1023/A:1023200000000).
- Ofman, L., Nakariakov, V.M., Deforest, C.E.: 1999, Slow Magnetosonic Waves in Coronal Plumes. *Astrophys. J.* **514**, 441. doi:[DOI](https://doi.org/10.1086/30750).
- Orrall, F.Q.: 1965, Observational Study of Macroscopic Inhomogeneities in the Solar Atmosphere.VI. Photospheric Oscillations and Chromospheric Structure. *Astrophys. J.* **141**, 1131. doi:[DOI](https://doi.org/10.1086/14830).
- O'Shea, E., Muglach, K., Fleck, B.: 2002, Oscillations above sunspots: Evidence for propagating waves? *Astron. Astrophys.* **387**, 642. doi:[DOI](https://doi.org/10.1051/0004-6361/200200037).
- Parnell, R.L., Beckers, J.M.: 1969, The Interpretation of Velocity Filtergrams. I: The Effective Depth of Line Formation. *Solar Phys.* **9**, 35–38. doi:[DOI](https://doi.org/10.1007/BF01353700).
- Reznikova, V.E., Shibasaki, K.: 2012, Spatial Structure of Sunspot Oscillations Observed with SDO/AIA. *Astrophys. J.* **756**, 35. doi:[DOI](https://doi.org/10.1088/0004-6372/756/1/35).

- Reznikova, V.E., Shibasaki, K., Sych, R.A., Nakariakov, V.M.: 2012, Three-minute Oscillations above Sunspot Umbra Observed with the Solar Dynamics Observatory/Atmospheric Imaging Assembly and Nobeyama Radioheliograph. *Astrophys. J.* **746**, 119. doi:[DOI](#).
- Rimmele, T.R.: 1995, Sun center observations of the Evershed effect. *Astrophys. J.* **445**, 511. doi:[DOI](#).
- Robbrecht, E., Verwichte, E., Berghmans, D., Hochedez, J.F., Poedts, S., Nakariakov, V.M.: 2001, Slow magnetoacoustic waves in coronal loops: EIT and TRACE. *Astron. Astrophys.* **370**, 591. doi:[DOI](#).
- Roupe van der Voort, L.H.M., Rutten, R.J., Sütterlin, P., Sloover, P.J., Krijger, J.M.: 2003, La Palma observations of umbral flashes. *Astron. Astrophys.* **403**, 277. doi:[DOI](#).
- Scherrer, P.H., Schou, J., Bush, R.I., Kosovichev, A.G., Bogart, R.S., Hoeksema, J.T., Liu, Y., Duvall, T.L., Zhao, J., Title, A.M., Schrijver, C.J., Tarbell, T.D., Tomczyk, S.: 2012, The Helioseismic and Magnetic Imager (HMI) Investigation for the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 207. doi:[DOI](#).
- Sheeley, N.R. Jr., Bhatnagar, A.: 1971, Measurements of the Oscillatory and Slowly-Varying Components of the Solar Velocity Field. *Solar Phys.* **18**, 379. doi:[DOI](#).
- Sigwarth, M., Mattig, W.: 1997, Velocity and intensity oscillations in sunspot penumbrae. *Astron. Astrophys.* **324**, 743.
- Teske, R.G.: 1974, Power spectra of velocity fluctuations in plages. *Solar Phys.* **39**, 79. doi:[DOI](#).
- Thomas, J.H., Cram, L.E., Nye, A.H.: 1982, Five-minute oscillations as a subsurface probe of sunspot structure. *Nature* **297**, 485. doi:[DOI](#).
- Tsiropoula, G., Alissandrakis, C.E., Mein, P.: 2000, Association of chromospheric sunspot umbral oscillations and running penumbral waves. I. Morphological study. *Astron. Astrophys.* **355**, 375.
- Tziotziou, K., Tsiropoula, G., Mein, N., Mein, P.: 2004, On the Nature of Chromospheric Umbral Flashes And Running Penumbral Waves (Abstract). In: Laskarides, P. (ed.) *Hellenic Astronomical Society Sixth Astron. Conf.*, Editing Office of the University of Athens, Athens, Greece, 50.

- Tziotziou, K., Tsiropoula, G., Mein, N., Mein, P.: 2006, Observational characteristics and association of umbral oscillations and running penumbral waves. *Astron. Astrophys.* **456**, 689. doi:[DOI](#).
- Vecchio, A., Cauzzi, G., Reardon, K.P., Janssen, K., Rimmele, T.: 2007, Solar atmospheric oscillations and the chromospheric magnetic topology. *Astron. Astrophys.* **461**, L1. doi:[DOI](#).
- Wang, T.J., Ofman, L., Davila, J.M.: 2009, Propagating Slow Magnetoacoustic Waves in Coronal Loops Observed by Hinode/EIS. *Astrophys. J.* **696**, 1448. doi:[DOI](#).
- Woods, T.N., Eparvier, F.G., Hock, R., Jones, A.R., Woodraska, D., Judge, D., Didkovsky, L., Lean, J., Mariska, J., Warren, H., McMullin, D., Chamberlin, P., Berthiaume, G., Bailey, S., Fuller-Rowell, T., Sojka, J., Tobiska, W.K., Viereck, R.: 2012, Extreme Ultraviolet Variability Experiment (EVE) on the Solar Dynamics Observatory (SDO): Overview of Science Objectives, Instrument Design, Data Products, and Model Developments. *Solar Phys.* **275**, 115. doi:[DOI](#).
- Yuan, D., Sych, R., Reznikova, V.E., Nakariakov, V.M.: 2014, Multi-height observations of magnetoacoustic cut-off frequency in a sunspot atmosphere. *Astron. Astrophys.* **561**, A19. doi:[DOI](#).
- Zhugzhda, Y., Sych, R.: 2014, Model of Local Oscillations in Sunspots. *Astron. Lett.* **40**, 576. doi:[DOI](#).
- Zirin, H., Stein, A.: 1972, Observations of Running Penumbral Waves. *Astrophys. J. Lett.* **178**, L85. doi:[DOI](#).